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Charged particle multiplicity distributions in Z^0 hadronic decays

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Abstract. This paper presents an analysis of the multiplicity distributions of charged particles produced in Z^0 hadronic decays in the DELPHI detector. It is based on a sample of 25364 events. The average multiplicity is $\langle n_{ch}\rangle = 20.71 \pm 0.04(\text{stat}) \pm 0.77(\text{syst})$ and the dispersion $D = 6.28 \pm 0.03(\text{stat}) \pm 0.43(\text{syst})$. The data are compared with the results at lower energies and with the predictions of phenomenological models. The Lund parton shower model describes the data reasonably well. The multiplicity distributions show approximate KNO-scaling. They also show positive forward-backward correlations that are strongest in the central region of rapidity and for particles of opposite charge.

1 Introduction

Results on charged particle multiplicity distributions in e^+e^- collisions [1–7] reveal interesting features. Among them are the rapid rise of the average charged multiplicity with increasing energy, the existence of forward-backward multiplicity correlations which are positive and almost energy independent and evidence for approximate KNO-scaling [8].

In this paper we report on properties of the charged particle multiplicity distributions from e^+e^- annihilation into hadrons studied in the DELPHI detector at LEP at center-of-mass energies, $\sqrt{s}$, between 91.0 and 91.5 GeV. We compare our results on multiplicity distributions of charged particles with those obtained in e^+e^- annihilation at lower energies, as well as with the expectations of the Lund parton shower model and other phenomenological models. Since our data are recorded at a much higher energy than those in earlier studies, it is of special interest to study the KNO-scaling properties and also the forward-backward multiplicity correlations.

In Sect. 2 we briefly describe the DELPHI detector and discuss our event sample, selection criteria, correction procedure and treatment of systematic errors. Experimental results on the charged multiplicities are presented in Sect. 3 and on the forward-backward multiplicity correlations in Sect. 4. Section 5 summarizes our conclusions.

2 Data selection

The data were recorded with the DELPHI detector at the CERN e^+e^- collider LEP. In the present paper a sample of 47400 events with $n_{ch} \geqq 5$ was used. A detailed description of the detector, of the trigger conditions and of the analysis chain can be found in [9]. Here only the specific properties relevant to the following analysis are summarized.

Charged particles were measured in the time projection chamber (TPC) as described in more detail in our previous paper [10] on global event shape distributions in the hadronic decays of the Z^0. Up to 16 space points in the TPC were used for track reconstruction by the DELPHI analysis package, DELANA [11]. The momentum resolution was found to be $\delta p/p^2 = \pm 0.012(\text{GeV/c})^{-1}$. Points on neighbouring tracks could be distinguished only if they were separated by at least 15 mm in z, the coordinate along the beam axis, and in $r\phi$, the azimuthal coordinate. No differences in track-finding efficiency were observed between the data and the Monte Carlo simulation.

The tracks of charged particles were retained only if:

(a) they extrapolated back to within 5 cm of the beam axis in r and to within 10 cm of the nominal crossing point in z,
(b) their momentum p was larger than 0.1 GeV/c,
(c) their measured track length was above 50 cm,
(d) their polar angle θ was between 25° and 155°.

Hadronic events were then selected by requiring that:

(a) the total energy of charged particles $E_{ch} = \sum_i E_i$ in each of the two hemispheres defined with respect to the beam axis exceeded 3 GeV, where E_i were the particle energies (assuming π mass),
(b) the total energy of charged particles seen in both hemispheres together exceeded 15 GeV,
(c) there were at least 5 charged particles with momenta above 0.2 GeV/c,
(d) the polar angle θ of the sphericity axis was in the range $50° < \theta < 130°$.

The resulting data sample comprised 25364 events. The last cut ensured that the retained events were well contained inside the TPC. After all four cuts, events due to beam-gas scattering and to $\gamma\gamma$ interactions were reduced to below 0.1% of the sample. The largest background was due to $\tau^+\tau^-$ events. From the Monte Carlo simulation this was calculated to be 0.15% of the sample.

The multiplicity distributions presented below are the result of correcting the raw data for limited geometrical acceptance and resolution of the TPC, limited efficiency of the track finding, particle interactions in the material of the detector, other detector imperfections, applied kinematical cuts, and also for QED initial state radiation. Like in our previous paper [10], the correction procedure was based on 50000 Monte Carlo events generated according to the Lund parton shower (PS) (Monte Carlo program JETSET version 6.3) model [12, 13]. Correction factors were obtained by comparing the ("true") distributions at the beginning of the simulation with the ("observed") distributions after reconstruction and selection. The "true" distributions were constructed from the final state particles of lifetime above 10^{-9} s which had not yet been tracked through the detector. The events were generated without initial state radiation. The charged particles from K_s^0 and Λ decays were included, irrespective of how far away from the interaction point the decay occured, while the charged particles from K_L^0 decay were not included. The "observed" distributions were constructed from the final state particles observed after tracking events, generated with initial state radiation, through the DELPHI detector to produce simulat-

ed raw data which were then processed through the same reconstruction and analysis programs as the real data.

The corrected multiplicity distribution was determined by unfolding the observed multiplicity distribution. Let $N_{obs}(n_{obs})$ be the number of accepted events with n_{obs} accepted charged tracks and $N_{tr}(n_{tr})$ be the corrected number of events with $n_{tr}(n_{tr}=\text{even})$ produced charged particles. The two distributions are related by the matrices M_1 and M_2:

$$N_{tr}(n_{tr}) = \sum_{n_{obs}} M_1(n_{tr}, n_{obs}) N_{obs}(n_{obs}), \quad (1)$$

$$N_{obs}(n_{obs}) = \sum_{n_{tr}} M_2(n_{obs}, n_{tr}) N_{tr}(n_{tr}) \quad (2)$$

with coefficients $M_1(n_{tr}, n_{obs})$ and $M_2(n_{obs}, n_{tr})$ determined using Monte Carlo events generated according to the Lund PS model. The matrix M_1 in (1) was used for the determination of the corrected multiplicity distributions. The matrix M_2 in (2) was used for the transformation of the multiplicity distributions predicted by models in order to compare them with the observed multiplicity distribution and calculate the corresponding χ^2. The matrix M_2 is straightforward to construct and is independent of the multiplicity distribution of the model used in the Monte Carlo simulation, but strongly dependent of the detector response as is desired. There is only a weak dependence on the kinematic variables generated by the model. The matrix M_1 is not taken as the inverse of M_2 since that would give rise to instabilities. It is therefore constructed from a preknowledge of the shape of the multiplicity distribution. Once a model has been tested using (2) and found to well represent the raw data, i.e. $N_{obs}(n_{obs})$, this model can be used in constructing the matrix M_1. Note that the reconstructed numbers of events with $n_{tr} \leqq 8$ are strongly model dependent in such a correction procedure.

The above procedure was applied to the multiplicity distribution in the full phase space and in the single hemisphere defined by the plane perpendicular to the sphericity axis.

The appropriate correction formalism for the analysis of forward-backward multiplicity correlations is a simple extension of formula (1) so the corrected two-dimensional multiplicity distribution reads:

$$N_{tr}(n_{F,tr}, n_{B,tr}) = \sum_{n_{F,obs}, n_{B,obs}} \cdot M(n_{F,tr}, n_{B,tr}, n_{F,obs}, n_{B,obs}) N_{obs}(n_{F,obs}, n_{B,obs}), \quad (3)$$

where n_F and n_B are the numbers of particles produced in the forward and backward hemispheres with respect to the sphericity axis. Since for e^+e^- collisions there is no difference between the "forward" and "backward" hemispheres, each event was entered twice.

Contributions to systematic errors arise from possible differences between the actual detector performance and that represented in the simulation program. To evaluate these, we tested the effects of a range of possible differences in the Monte Carlo simulation, such as additional momentum smearing, a constant sagitta shift and a different drift velocity inside the TPC. We also varied our selection criteria over a wide range. The matrices $M_1(n_{tr}, n_{obs})$, $M_2(n_{obs}, n_{tr})$ and $M(n_{F,tr}, n_{B,tr}, n_{F,obs}, n_{B,obs})$ were also evaluated using the Marchesini-Webber PS model [14] and the Lund Matrix Element (ME) (Monte Carlo program JETSET version 7.2) model [15, 13] with parameters optimized at $\sqrt{s}=91$ GeV [16]. The variance of the M values computed from the three different models* was taken as one contribution to the systematic uncertainty.

3 Full phase space and single hemisphere charged multiplicity distributions

The charged multiplicity distribution for the raw data is shown in Table 1. The corrected charged particle multiplicity distributions for full phase space and single hemisphere are presented in Table 2 and shown in Fig. 1. The average charged multiplicity $\langle n_{ch} \rangle$, the dispersion $D=(\langle n_{ch}^2 \rangle - \langle n_{ch} \rangle^2)^{1/2}$, the ratio $\langle n_{ch} \rangle / D$ and the normalized moments $C_l = \langle n_{ch}^l \rangle / \langle n_{ch} \rangle^l$ for both distributions are given in Table 3. The quoted errors are calculated from the statistical errors and from the correction procedure. The values of $\langle n_{ch} \rangle$ and D in Table 3 are reduced by 2% due to a correction for electrons from photon conversions before the TPC which are not accounted for in the Monte Carlo. This correction was not applied to the multiplicity distributions given in Table 2. We take this 2% into account as additional systematic uncertainty.

Table 1. The charged particle multiplicity distribution for the raw data in the full phase space

No. charged particles	No. events	No. charged particles	No. events
5	46	27	459
6	93	28	380
7	180	29	293
8	291	30	250
9	507	31	201
10	717	32	129
11	1026	33	116
12	1300	34	74
13	1527	35	51
14	1728	36	43
15	1855	37	19
16	1834	38	13
17	1829	39	13
18	1717	40	7
19	1644	41	6
20	1485	42	7
21	1292	43	3
22	1107	44	3
23	1053	45	3
24	822	47	2
25	666	51	1
26	572		

* The variance for optimized Lund ME is smaller than for untuned standard Lund ME

Table 2. Charged particle multiplicity distributions $P(n)=\frac{1}{N}\frac{dN}{dn}$ (%) for full phase space and single hemisphere. Errors include systematics. The 2% correction for excess electrons from photon conversions is not included.

n	$P(n)$ (full phase space)	n	$P(n)$ (single hemisphere)
2	(0.001 ± 0.001)[a]	1	0.124 ± 0.020
4	(0.025 ± 0.008)[a]	2	0.466 ± 0.065
6	0.155 ± 0.040	3	$1.21\ \pm0.17$
8	0.674 ± 0.055	4	$2.67\ \pm0.10$
10	$2.28\ \pm0.16$	5	$4.56\ \pm0.17$
12	$4.85\ \pm0.28$	6	$7.04\ \pm0.26$
14	$8.22\ \pm0.44$	7	$8.58\ \pm0.31$
16	$11.10\ \pm0.58$	8	$9.97\ \pm0.36$
18	$12.90\ \pm0.66$	9	$10.20\ \pm0.36$
20	$13.10\ \pm0.67$	10	$9.87\ \pm0.35$
22	$11.70\ \pm0.60$	11	$8.85\ \pm0.32$
24	$9.79\ \pm0.51$	12	$7.83\ \pm0.28$
26	$7.53\ \pm0.40$	13	$6.44\ \pm0.23$
28	$5.76\ \pm0.31$	14	$5.19\ \pm0.19$
30	$4.14\ \pm0.23$	15	$4.14\ \pm0.15$
32	$2.93\ \pm0.17$	16	$3.22\ \pm0.12$
34	$1.88\ \pm0.11$	17	2.490 ± 0.094
36	1.220 ± 0.080	18	1.980 ± 0.077
38	0.755 ± 0.056	19	1.400 ± 0.056
40	0.478 ± 0.100	20	1.040 ± 0.140
42	0.251 ± 0.060	21	0.760 ± 0.100
44	0.143 ± 0.035	22	0.591 ± 0.081
46	0.082 ± 0.021	23	0.426 ± 0.059
48	0.020 ± 0.006	24	0.285 ± 0.040
50	0.011 ± 0.017	25	0.212 ± 0.031
52	0.006 ± 0.005	26	0.128 ± 0.019
		27	0.076 ± 0.014
		28	0.041 ± 0.007
		29	0.042 ± 0.021
		30	0.015 ± 0.007
		31	0.015 ± 0.005
		32	0.007 ± 0.001
		33	0.003 ± 0.001
		34	0.006 ± 0.007

[a] Not measured, taken from the Lund PS model

Table 3. Moments for full phase space and single hemisphere charged particle multiplicity distributions. The first error is statistical, the second is systematic

Moment	Full phase space	Single hemisphere
$\langle n\rangle$	$20.71\ \pm0.04\ \pm0.77$	$10.35\ \pm0.02\ \pm0.47$
D	$6.28\ \pm0.03\ \pm0.43$	$4.19\ \pm0.02\ \pm0.32$
$\langle n\rangle/D$	$3.30\ \pm0.02\ \pm0.20$	$2.47\ \pm0.01\ \pm0.20$
C_2	$1.092\pm0.003\pm0.03$	$1.164\pm0.003\pm0.03$
C_3	$1.293\pm0.003\pm0.03$	$1.544\pm0.006\pm0.04$
C_4	$1.647\pm0.009\pm0.04$	$2.296\pm0.018\pm0.06$
C_5	$2.245\pm0.017\pm0.06$	$3.770\pm0.051\pm0.09$

Our value of the average charged multiplicity $\langle n_{ch}\rangle = 20.71\pm0.04(\text{stat})\pm0.77(\text{syst})$ agrees well with the previous value of DELPHI [10] and with those corrected values $\langle n_{ch}\rangle$ at $\sqrt{s}=91$ GeV presented by ALEPH [17], MARK 2 [18] and OPAL [19]. The values of $\langle n_{ch}\rangle$ measured by DELPHI and by other e^+e^- experiments [1–7, 17–19] are shown in Fig. 2. For all of the e^+e^-

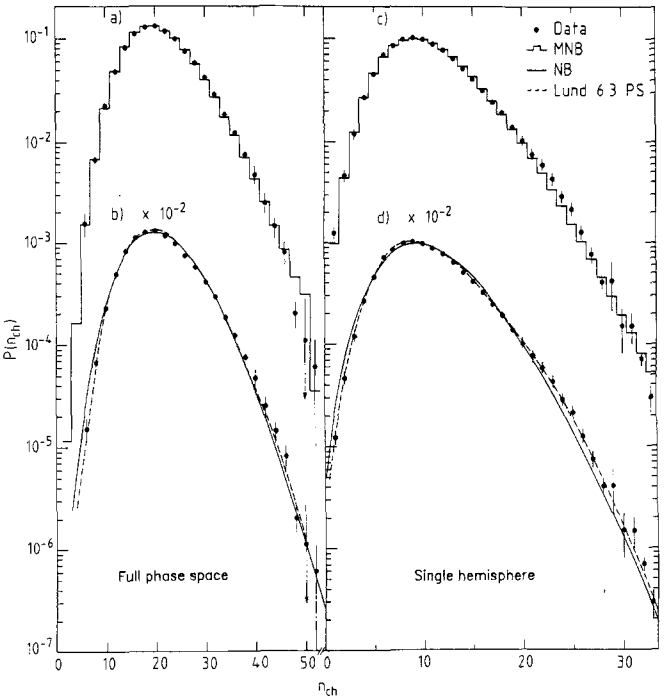

Fig. 1a–d. Corrected charged particle multiplicity distributions (full dots) for **a**, **b** full phase space and **c**, **d** single hemisphere compared with the Lund PS (JETSET 6.3) model predictions (**b**, **d**, dashed curves), with the fits to the NB distribution (**b**, **d**, solid curves) and to the Modified NB distribution [32] (**a**, **c**, histograms)

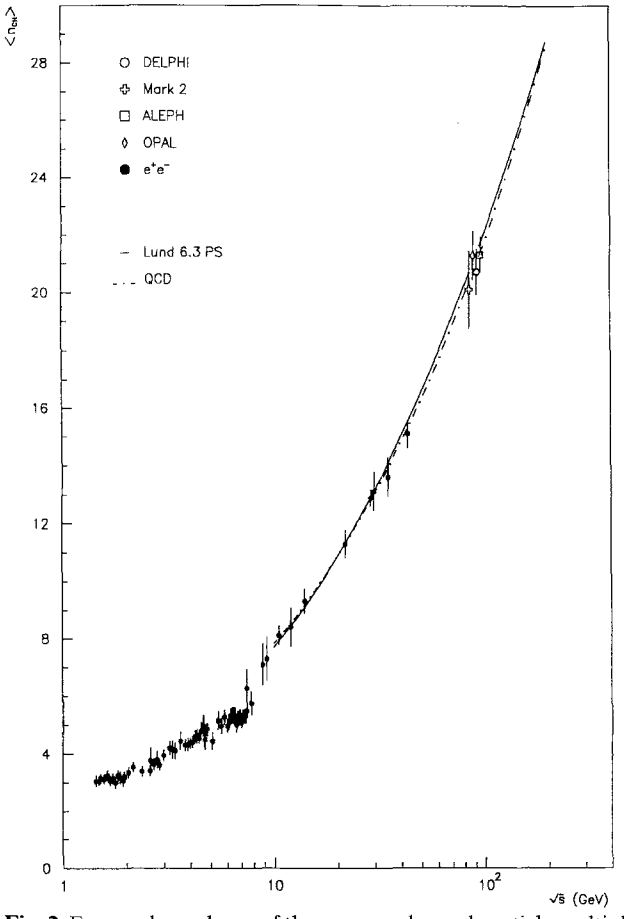

Fig. 2. Energy dependence of the average charged particle multiplicity in e^+e^- collisions. The data at lower energies are taken from [1–7, 17–19]. Solid curve is the prediction of the Lund PS (JETSET 6.3). Dash-dotted curve is the result of the fit to the QCD-inspired formula (4) (see the text)

data shown in Fig. 2 and used in the following fits, the average multiplicity value includes the charged secondaries of K_s^0, Λ and $\bar{\Lambda}$ decays.

The fits to our values of $\langle n_{ch}\rangle$ and other available e^+e^- data [1–7, 17–19] as a function of energy using various parametrizations give results which are not very different from those obtained recently by TASSO [1] at lower energy. We find:

– for $\langle n_{ch}\rangle = a + b\cdot\ln(s) + c\cdot\ln^2(s)$:
$a = 3.320 \pm 0.083$, $b = -0.408 \pm 0.055$, $c = 0.263 \pm 0.008$ with $\chi^2/NDF = 79/69$;
– for $\langle n_{ch}\rangle = a\cdot s^b$:
$a = 2.228 \pm 0.026$, $b = 0.249 \pm 0.002$ with $\chi^2/NDF = 153/70$;
– for $\langle n_{ch}\rangle = a + b\cdot\exp(c\sqrt{\ln(s/Q_0^2)})$ at $Q_0^2 = 1\,\mathrm{GeV}^2$:
$a = 2.527 \pm 0.072$, $b = 0.094 \pm 0.010$, $c = 1.775 \pm 0.038$ with $\chi^2/NDF = 92/69$.*

One sees that with the new LEP data it is now possible to exclude the power law dependence $\langle n_{ch}\rangle = a\cdot s^b$.

We have also fitted the data presented in Fig. 2 in the energy range from 10 to 91 GeV to the form

$$\langle n_{ch}\rangle = a\cdot\alpha_s^b\cdot\exp(c/\sqrt{\alpha_s})(1 + O(\sqrt{\alpha_s})) \quad (4)$$

which was obtained in [20, 21] on a basis of QCD in the next-to-leading order. The running coupling constant in (4) was taken as

$$\frac{\alpha_s(s)}{4\pi} = \frac{1}{\beta_0 \ln(s/\Lambda^2)} - \frac{\beta_1 \ln\ln(s/\Lambda^2)}{\beta_0^3 \ln^2(s/\Lambda^2)}. \quad (5)$$

Here a is a normalization constant and the parameters β_0, β_1, b and c are fixed at the values $\beta_0 = 11 - 2N_f/3 = 7.67$, $\beta_1 = 102 - 38N_f/3 = 38.67$, $b = 1/4 + (10N_f)/(27\beta_0) = 0.49$ and $c = \sqrt{96\pi/\beta_0} = 2.27$ for $N_f = 5$ [21]. According to [21] one can neglect the $O(\sqrt{\alpha_s})$ term in (4) and treat a and Λ as free parameters. The fit (shown by the dash-dotted curve in Fig. 2) gives very good agreement with the data ($\chi^2/NDF = 2.3/11$). The best values of the parameters are $a = 0.066 \pm 0.013$ and $\Lambda = 138 \pm 62$ MeV. As explained in [21], Λ is a process-dependent quantity not necessarily equal to $\Lambda_{\overline{MS}}$. However it is expected to be close to $\Lambda_{\overline{MS}}$ if the $O(\sqrt{\alpha_s})$ correction does turn out to be small.

From Fig. 1 (dashed curves) and Fig. 2 (continuous curve) one sees that the Lund PS (JETSET 6.3) model [12, 13] describes the e^+e^- data reasonably well. The fits to the raw multiplicity data of the Lund PS model, transformed according to (2) for detector response, are reasonably good, giving $\chi^2/NDF = 64/36$ for full phase space and $\chi^2/NDF = 47/25$ for single hemisphere.** These results are of interest in view of the physics content of the Lund PS model [22, 23, 12, 13]. The model contains three separate phases. First, there is the hard scattering phase, treated perturbatively, during which parton showers develop in QCD branching processes (quark bremsstrahlung, gluon bremsstrahlung and quark pair production). These processes are cut-off at a virtuality of $Q_0 = 1$ GeV. The subsequent phase treats the non-perturbative, soft processes according to the Lund string fragmentation model, which transforms the multiparton state created by the first phase into hadrons. Finally, resonances and shortlived particles are allowed to decay into the final state particles, which correspond to the ones available for observation. At low c.m. energies the soft processes are dominating, whereas at such high energy as the one under present study the multiplicity fluctuations are mainly controlled by the hard processes. It is therefore of great interest to note that the model is able to describe the data reasonably well without any tuning of parameters.

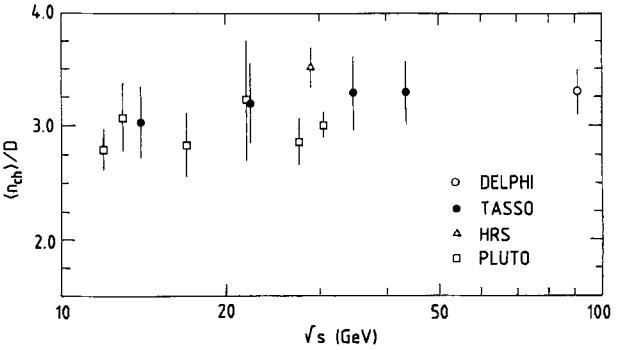

Fig. 3. Energy dependence of $\langle n_{ch}\rangle/D$ measured by DELPHI, TASSO [1], HRS [7] and PLUTO (the PLUTO points are taken from [1]). The DELPHI and TASSO points are shown with their systematic and statistical errors

The ratio $\langle n_{ch}\rangle/D$ for the full phase space multiplicity distribution is shown as a function of energy in Fig. 3.* It is energy independent, within the statistical and systematic errors. The ratio of $\langle n_{ch}\rangle/D$ for full phase space to that for single hemisphere is $1.34 \pm 0.01 \pm 0.04$ for the DELPHI data and it too is energy independent. Indeed TASSO [1] gives for this ratio: 1.35 ± 0.03, 1.35 ± 0.03, 1.34 ± 0.01 and 1.35 ± 0.02 at 14, 22, 34.8 and 43.6 GeV, respectively. All these values are lower than the value of $\sqrt{2}$ expected for two-jet events, if the jets are produced independently, as predicted in some phenomenological approaches [24] for the high LEP energies. The predictions of the Lund PS model agree well with the DELPHI values of $\langle n_{ch}\rangle/D$ for full phase space and single hemisphere distributions, the Lund PS model giving 3.39 ± 0.01 and 2.47 ± 0.01, respectively.

Energy independence of the ratio $\langle n_{ch}\rangle/D$ suggests a KNO-scaling property [8] of the multiplicity distribution. KNO-scaling implies an energy independence of the normalized moments C_l (we recall that $\langle n_{ch}\rangle/D = (C_2 - 1)^{-1/2}$) and of the function $\psi(z) = \langle n_{ch}\rangle P(n_{ch})$ plotted versus a variable $z = n_{ch}/\langle n_{ch}\rangle$. The normalized moments of the full phase space and single hemisphere distributions are shown as functions of c.m. energy in Fig. 4. There is no indication of an energy variation of

* With the parameter c fixed at the value $c = \sqrt{72/(33 - 2N_f)}$, the number of flavours N_f chosen equal to the TASSO values [1] and Q_0 free, we obtain $a = 2.122 \pm 0.134$, $b = 0.049 \pm 0.009$, $Q_0 = 0.306 \pm 0.098$ GeV with $\chi^2/NDF = 51/69$

** Although χ^2 contains not only statistical errors we consider a fit with a χ^2-probability larger than 0.1% as acceptable

* The PLUTO points here and elsewhere are taken from [1]

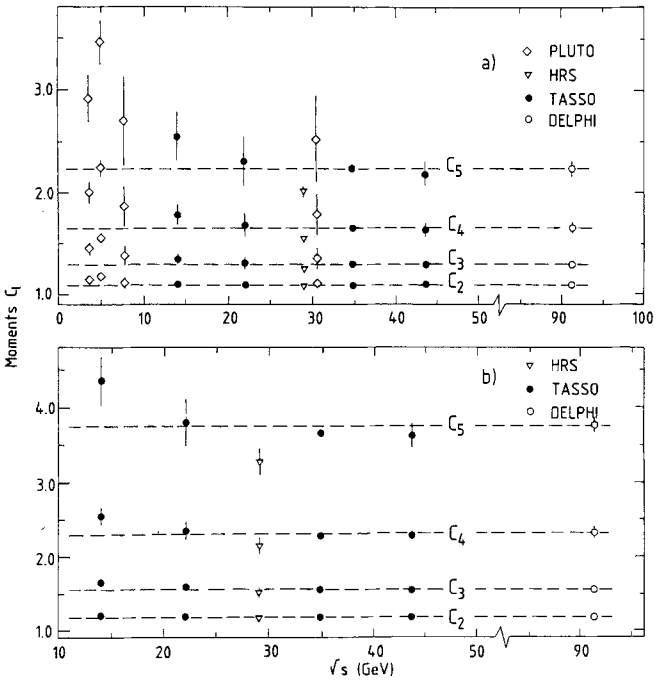

Fig. 4a, b. Energy dependence of the normalized moments C_l for **a** full phase space and **b** single hemisphere multiplicity distributions measured by DELPHI, TASSO [1], HRS [7] and PLUTO (the PLUTO points are taken from [1]). Dashed lines C_l=const are drawn through the DELPHI points

C_2 to C_5 for c.m. energies larger than about 20 GeV. The KNO-functions $\psi(z)$ for the DELPHI and lower energy data starting from $\sqrt{s}=14$ GeV are shown in Fig. 5. They also support approximate scaling.*

In the Lund model, which generally agrees well with data at all energies in the presently available range of energies, the hard processes tend to broaden the multiplicity distribution in terms of the KNO-variable z as the energy is increased, whereas the soft processes lead to a narrowing (since it is almost Poissonian at fixed number of partons). The two opposing trends combine in such a way that an approximate KNO-scaling holds. At least the $D/\langle n\rangle$ ratio remains almost constant in the energy range 15–1000 GeV [25]. The trend seen in [25] indicates a broadening in the z-variable at energies much beyond 1 TeV and this is further supported by Lund model simulations made at very high energies [26]. Also it has been proven [27–30] that a broad class of branching processes exibit KNO-like scaling. All this agrees with the experimental observation of approximate KNO-scaling in the energy interval from 20 GeV to 91 GeV. Notice, however, that based on the geometrical model of multiparticle production Chou and Yang [31] expect in e^+e^- a Poisson distribution and thus no KNO-scaling. Their statement is strictly limited to two-jet events.

Successful fits of the negative binomial (NB) distribution have been made to data at lower energies. Reasonably good agreements have also been obtained to simulat-

* Note that the DELPHI points at the two smallest z values corresponding to multiplicities $n\leqq 8$ are strongly affected by the correction procedure and should be treated with caution

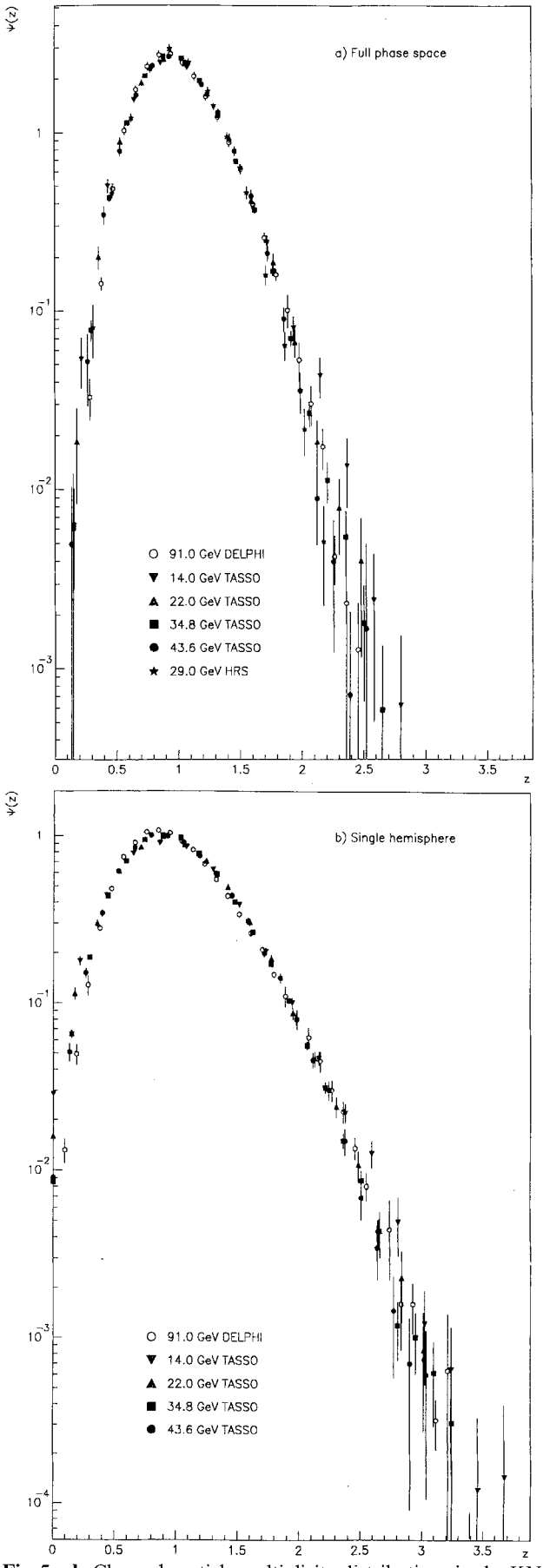

Fig. 5a, b. Charged particle multiplicity distributions in the KNO-variables $\psi(z)=\langle n_{ch}\rangle P(n_{ch})$ versus $z=n_{ch}/\langle n_{ch}\rangle$ for **a** full phase space and **b** single hemisphere measured by DELPHI in comparison with TASSO [1] and HRS [7] data

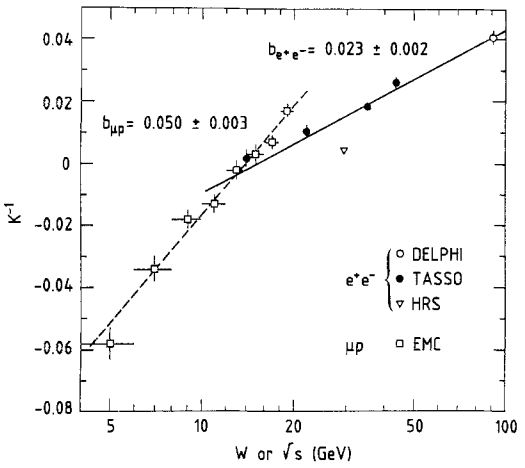

Fig. 6. Energy dependence of the NB parameter k^{-1} resulting from fits to charged multiplicity distributions in full phase space for e^+e^- and μ^+p [34] collisions. The e^+e^- data at lower energies are taken from [1, 7]. The straight lines are fits to the form $k^{-1}=a+b\cdot\ln(\sqrt{s}/Q_0)$ ($k^{-1}=a+b\cdot\ln(W/Q_0)$) with the best values of b as indicated

ed data from the Lund model [26] at low as well as very high energies. The fit to our data by the NB distribution*

$$P_n(m,k)=\frac{k(k+1)\ldots(k+n-1)}{n!(1+m)^k}\left(\frac{m}{1+m}\right)^n, \tag{6}$$

where m and k are positive parameters and $m=\langle n\rangle/k$, gives $k^{-1}=0.0411\pm0.0012$, $m=0.879\pm0.025$ with $\chi^2/NDF=80/34$ for the full phase space and $k^{-1}=0.0664\pm0.0017$, $m=0.705\pm0.017$ with $\chi^2/NDF=66/23$ for the single hemisphere.** The NB distribution (solid curves in Fig. 1b, d) describes the data, but less successfully than the Lund PS model. Better agreement with the data is obtained for the modified negative binomial (MNB) distribution [32], characterized by the generating function

$$M(x)=\left(\frac{1+\Delta(1-x)}{1+m(1-x)}\right)^k, \tag{7}$$

where $m=\Delta+\langle n\rangle/k$, with three fitted parameters $k=7.92\pm0.31$, $m=0.644\pm0.028$, $\Delta=-0.696\pm0.024$ with $\chi^2/NDF=43/33$ for the full phase space*** and $k=6.38\pm0.26$, $m=1.172\pm0.035$, $\Delta=-0.483\pm0.035$ with $\chi^2/NDF=59/22$ for a single hemisphere. These fits are shown by the histograms in Fig. 1a, c.

The NB parameter k^{-1} for the multiplicity distribution in full phase space measured by DELPHI is compared with those at lower energies [1, 7] in Fig. 6. A phenomenological fit of the form

$$k^{-1}=a+b\cdot\ln(\sqrt{s}/Q_0) \tag{8}$$

(with $Q_0=1$ GeV) gives $a=-0.063\pm0.005$ and $b=0.023\pm0.002$ with $\chi^2/NDF=2.2/3$ (the HRS value of the k^{-1} given in [7] without error and not consistent with the trend of other data has not been used in the fit). In the same Fig. 6 we also show the recent EMC Collaboration data [34] on k^{-1} for μ^+p interactions versus total hadronic energy W. Fitting them to the form $k^{-1}=a+b\cdot\ln(W/Q_0)$ we obtain $a=-0.133\pm0.007$, and $b=0.050\pm0.003$ with $\chi^2/NDF=6.6/6$. For $pp(\bar{p}p)$ data over the c.m. energy range from 10 to 900 GeV, the UA5 Collaboration obtained $a=-0.104\pm0.004$ and $b=0.058\pm0.001$ [35]. Thus the slopes b for $pp(\bar{p}p)$ and μ^+p data are close to each other but significantly higher than for e^+e^- collisions.*

We have also compared the multiplicity distribution with the model of Ellis et al. [37] based on the idea that near-mass-shell ("cool") partons produced by conventional perturbative QCD showering break chiral symmetry spontaneously and independently when they convert non-perturbatively into hadrons. The average charged multiplicity $\langle n_{ch}\rangle=21.9$ predicted by Ellis et al. for all events agrees with experiment. Their predictions $\langle n_{ch}\rangle=31.5(20.5)$ for events with sphericity S above and below 0.15 can be compared with the corresponding measured values of $26.8\pm0.1\pm0.8$ ($19.7\pm0.1\pm0.6$). Although the data reflect the predicted trend towards higher multiplicity in higher sphericity events, the model is quantitatively unaccurate. Moreover the charged multiplicity distribution obtained in the model using all links in a triangulation of space with "cool" partons as vertices is significantly broader than the data.

4 Forward-backward multiplicity correlations

To study the correlations between particles produced in the different c.m.s. hemispheres, forward (F) and backward (B), one measures the average charged multiplicity in one hemisphere as a function of the charged multiplicity in the opposite one, $\langle n_F\rangle$ versus n_B, or vice versa. Correlations are usually parametrized as

$$\langle n_F\rangle=a+b\cdot n_B, \tag{9}$$

where b measures the correlation strength. In hadron-hadron collisions, clear evidence exists for strong F-B correlations with b rising with increasing energy as $\ln(s)$ (see, for example [38] and Refs. therein). New precise TASSO data have established weak, positive and approximately energy independent F-B correlations from $\sqrt{s}=14$ GeV to 46.8 GeV [1]. However the HRS Colla-

* In the NB fit to the multiplicity distribution for the full phase space we used the normalized even component of the NB

** This and all other parametrizations of multiplicity distribution were fitted to the observed data using the relation (2). In these fits the systematic uncertainty was taken into account and the bins on the tails of observed distributions were combined

*** We fitted the distribution of negatively charged particles following the arguments of Szwed et al. [33]

* A significantly larger slope value $b=0.046\pm0.002$ for e^+e^- collisions obtained earlier [36] and used by the EMC Collaboration [34] is based on the fit to the less precise e^+e^- data at lower energy

Table 4. Fitted values of the correlation strength parameter b in $\langle n_F \rangle = a + b \cdot n_B$ for all and for unlike sign charged particles obtained by TASSO [1], HRS [7, 39] and in the present experiment

	$\sqrt{s}$ (GeV)	b (all particles)	b (unlike sign particles)
TASSO	14.0	0.085 ± 0.014	0.306 ± 0.010
TASSO	22.0	0.084 ± 0.016	0.251 ± 0.013
HRS	29.0	-0.001 ± 0.015	
TASSO	34.8	0.089 ± 0.003	0.226 ± 0.003
TASSO	43.6	0.111 ± 0.009	0.200 ± 0.009
DELPHI	91.0	0.118 ± 0.009	0.177 ± 0.009

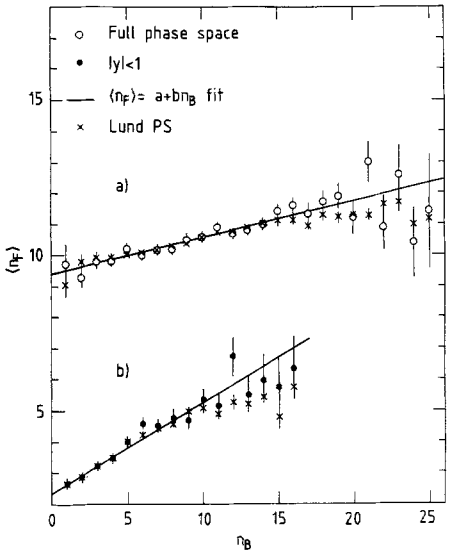

Fig. 7a, b. Forward-backward charged particle multiplicity correlations, $\langle n_F \rangle$ versus n_B, measured by DELPHI **a** in the full phase space (open dots) and **b** in the central $|y|<1$ region (full dots) together with straight line fits and the Lund PS (JETSET 6.3) model predictions (stars)

boration with their high statistics data at $\sqrt{s}=29$ GeV [7, 39] sees no evidence for correlations (see Table 4).

The variation of $\langle n_F \rangle$ with n_B measured by DELPHI is shown in Fig. 7a. In agreement with TASSO [1], but contrary to the HRS results [7, 39], we find a slow rise of $\langle n_F \rangle$ with increasing n_B. The fit of the form (9) (straight line in Fig. 7a) gives the values $b=0.118 \pm 0.009$ with $\chi^2/NDF=25/23$. As one can see from Fig. 7a, the Lund PS model provides a good description of the data. Fitting the Lund PS model points gives $b=0.091 \pm 0.004$ and $\chi^2/NDF=42/23$. Our value of the correlation strength parameter b when compared with the TASSO values (see Table 4, second column) exhibits, within errors, no energy variation from $\sqrt{s}=14$ GeV to 91 GeV.

We find that the F-B correlations are strongest in the central region, defined by the c.m. rapidity cut $|y| \leqq 1$.* The dependence of $\langle n_F \rangle$ on n_B for this region is also shown in Fig. 7b. The fit of the form (9) (straight line in Fig. 7b) gives in this case: $b=0.289 \pm 0.012$ with

* In calculating the rapidity $y=1/2 \ln((E+p_L)/(E-p_L))$, the p_L was taken as the momentum component parallel to the sphericity axis, and the pion mass was assigned to all particles

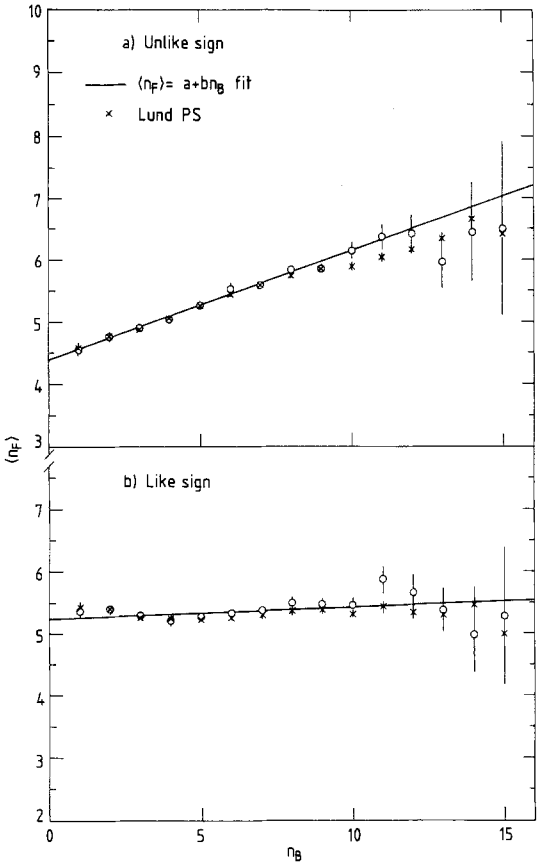

Fig. 8a, b. Forward-backward charged particle multiplicity correlations measured by DELPHI for **a** unlike sign and **b** like sign charged particles in the full phase space (open dots) together with straight line fits and the Lund PS (JETSET 6.3) model predictions (stars)

$\chi^2/NDF=28/14$. The Lund PS model is again well consistent with the data. Outside the central region, i.e. for $|y|>1$, the correlations are small; the fit gives $b=0.057 \pm 0.008$ with $\chi^2/NDF=14/16$.

We also find, in agreement with earlier results of the NA22 [38] and TASSO [1] Collaborations, that the F-B correlations are dominated by the correlations between unlike sign $(+-)$ charged particles. This is clearly seen from Fig. 8, where we show the dependence of $\langle n_F \rangle$ on n_B for the unlike sign and like sign $(++$ or $--)$ particles together with the results of fits of the form (9) (straight lines) and the Lund PS model predictions. For unlike sign particles $b=0.177 \pm 0.009$. Table 4 (third column) shows that this parameter decreases with increasing energy. For like sign particles, the correlation strength $b=0.020 \pm 0.006$ is significantly smaller (the Lund PS model gives $b=0.009 \pm 0.003$). Applying the rapidity cut $|y| \leqq 1$ for unlike and like sign particles gives $b=0.350 \pm 0.015$ and $b=0.210 \pm 0.013$, respectively.

5 Summary and conclusions

In the present paper, the charged particle multiplicity distributions at $\sqrt{s}=91$ GeV measured in the DELPHI experiment at LEP have been analysed. Our main con-

clusions based on 25364 events after the cuts, can be summarized as follows:

– The average charged particle multiplicity is $\langle n_{ch}\rangle = 20.71 \pm 0.04(\text{stat}) \pm 0.77(\text{syst})$ and the dispersion $D = 6.28 \pm 0.03(\text{stat}) \pm 0.43(\text{syst})$.

– The Lund parton shower model describes all of the studied features of the charged particle multiplicity distributions at $\sqrt{s} = 91$ GeV.

– Forward-backward correlations exist in e^+e^- collisions at $\sqrt{s} = 91$ GeV. They are positive, strongest in the central $|y| < 1$ region and larger for the particles of opposite charge.

– The charged multiplicity distributions for full phase space and single hemisphere are described by the negative binomial and modified negative binomial distributions. The energy dependence of the NB parameter k^{-1} for e^+e^- collisions can be parametrized by the form (8), but with a slope value only half that for $\mu^+ p$ and $pp(\bar{p}p)$ collisions.

When further comparing the DELPHI results with those at lower energies, we conclude:

– The energy dependence of the average charged multiplicity for e^+e^- collisions is well described by the parametrizations $\langle n_{ch}\rangle = a + b \cdot \ln(s) + c \cdot \ln^2(s)$ and $\langle n_{ch}\rangle = a + b \cdot \exp(c\sqrt{\ln(s/Q_0^2)})$, suggested respectively by the analysis of $pp(\bar{p}p)$ data and by QCD. The power law $\langle n_{ch}\rangle = a \cdot s^b$ suggested by the hydrodynamical models is practically exluded. The expression $\langle n_{ch}\rangle = a \cdot \alpha_s^b \cdot \exp(c/\sqrt{\alpha_s})$ with the running coupling constant $\alpha_s(s)$ in the form (5) deduced on a basis of QCD in next-to-leading order describes the data very well; the best value of the process-dependent QCD parameter Λ is 138 ± 62 MeV.

– The charged multiplicity distribution for e^+e^- collisions from $\sqrt{s} \approx 20$ to 91 GeV shows approximate KNO-scaling. This is seen from the energy independence of the normalised moments $C_2 - C_5$ and of the KNO-function $\psi(z)$.

After this paper was ready for publication we received an AMY Preprint [40] which reaches similar conclusion in KNO-scaling.

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